Monitor Soil Salinity to Evaluate Irrigation/Drainage Adequacy

Traditionally, the concepts of leaching requirement (LR) and salt-balance-index (SBI) have been used to judge the adequacy and appropriateness of irrigation and drainage systems, operations and practices with respect to salinity control, water use efficiency and irrigation sustainability (U. S. Salinity Laboratory Staff, 1954). However, these latter approaches are inadequate for these purposes. There are many reasons for this conclusion; some are given in the following paragraphs.

The leaching requirement, which refers to the amount of leaching required to prevent excessive loss in crop yield caused by salinity buildup within the rootzone from the irrigation water per se, is a "concept" based on assumptions of steady-state and absolutely uniform conditions of irrigation, infiltration and evapotranspiration, none of which is achieved in most field situations which, typically, are dynamic and variable, both spatially and temporally. Salt buildup in the rootzone caused by "subbing" of water from a shallow, water table is not accounted for in this concept nor is it in the traditional method for determining the SBI. Additionally, there is no practical way to directly measure the degree of leaching being achieved in a field, much less in the various parts of a field, in order to determine its uniformity, adequacy and appropriateness. On the other hand, it is possible to measure soil salinity and its distribution within a field and through the rootzone and, from this information, to assess whether it is within acceptable limits for crop production and to infer whether leaching is adequate and uniform, or not, anywhere in a field and likewise to assess whether drainage is adequate, since salinity is a tracer of the net processes of infiltration, leaching, evapotranspiration and drainage. In fact, the concentration and distribution of salinity through the rootzone is a direct reflection of the net interaction of these processes and gives you a meaningful measure of the adequacy/appropriateness of irrigation/drainage. The magnitude and distribution of salinity within the field and the soil profile provide direct information of the uniformity and direction of net water flux and hence of the adequacy of the irrigation/drainage system in the field (Rhoades, 1976, 1980, 1992a). Thus, I recommend that direct monitoring of rootzone salinity levels and distributions across fields be undertaken periodically to evaluate the effectiveness of salinity, irrigation and drainage management programs (Rhoades, 1978, 1979; Rhoades, et.al., 1997).

As explained earlier, the salt-balance index, which refers to the net difference between salt added to an irrigation project in the irrigation water and that removed in its drainage effluent, has been traditionally used to evaluate the adequacy/appropriateness of leaching, irrigation and drainage practices at the project scale. This approach is inadequate for these purposes because it provides no information about the absolute level of salinity within the rootzones of any crop or specific field within the project. Nor does it provide a realistic measure with which to judge whether, or not, the project is trending towards an increase, or decrease, in salinity within the rootzone, because salinity from below the soil profile and of geologic origin is typically contained in the drainage water collected from the subsurface drain system (Rhoades, 1974; Kaddah and Rhoades, 1976). Additionally, the transit times involved in the drainage flows resulting from a given irrigation event are so long (usually more than 25 years) that the index values are not reflective of current trends (Jury, 1975a, 1975b).

Thus, I conclude that the effectiveness of irrigation & drainage design and management and of water-table & salinity control can not be achieved using LR and SBI concepts. I also conclude that periodic information of soil salinity levels and distributions within the crop rootzones and fields of the project is practical to obtain and useful to inventory conditions of soil salinity, to assess the adequacy of leaching and drainage and to guide management practices. Such information can also be used to delineate the diffuse source-areas of salt-loading within irrigated lands and to map the distribution and extent of drainage problem areas.

In my opinion, the proper management of soil and water salinity requires the following: 1) an adequate knowledge of the level, extent, magnitude and distribution of rootzone soil salinity in the fields of the irrigation project (a suitable inventory of conditions); 2) the ability to be able to detect changes and trends in the status of soil salinity over time and the ability to determine the impact of management changes upon the conditions (a suitable monitoring program); 3) the ability to identify salinity problems and their underlying/inherent causes, both natural and management-induced (a suitable means of detecting & diagnosing problems and identifying their causes); 4) a means to evaluate the adequacy and effectiveness of on-going irrigation and drainage systems, operations and practices with respect to controlling soil salinity, conserving water supplies and protecting water quality from excessive salinization (a suitable means of evaluating management practices), and 5) the ability to determine the areas in fields and in irrigation projects where excessive deep percolation is occurring, i.e., where the water- and salt-loading contributions to the underlying groundwater are coming from (a suitable means of determining areal sources of pollution). I refer to the above set of measurement-related techniques and methods and the means of evaluation of adequacy & appropriateness, as "salinity assessment" (Rhoades, et al., 1997). I believe that the countries of the world with salinity problems should implement assessment programs which provide the above information in a timely and efficient way. Smedema (1995) has similarly concluded that " in many developing countries policy formulation and project preparation are severely handicapped by lack of reliable information on the nature and extent of the affected area. Salinity is a highly variable condition and difficult to monitor and to map with presently used observation methods. Development of suitable remote sensing methods, therefore, would be of considerable aid to countries in their combat of the problem of waterlogging and salination of irrigated land."

The achievement of an assessment technology such as the above begins with a practical methodology for measuring soil salinity in the field, which is complicated by its spatially variable and dynamic nature caused by the effects and interactions of varying edaphic factors (soil permeability, water table depth, salinity of perched groundwater, topography, soil parent material, geohyrology), management induced processes (irrigation, drainage, tillage, cropping practices), as well as by climate-related factors (rainfall, amount and distribution, temperature, relative humidity, wind). When the need for repeated measurements and extensive sampling requirements are met, the expenditure of time and effort to characterize and map a field's or project's salinity condition with conventional soil sampling and laboratory-analysis procedures becomes prohibitive. A more rapid, field-measurement technology is needed. This assessment technology should account for the spatial location of the measurement sites involved with the required large intensive and extensive data sets, it should provide a systematic methodology for evaluating management effects, and it should be able to detect changes or differences occurring in an areas salinity condition over both time and space.

Over the course of many years I, with the help of my colleagues, have been developing such a technology. It is now mostly completed. It is an integrated system comprised of rapid, mobile instrumental techniques for measuring bulk soil electrical conductivity (EC_a) directly in the field as a function of spatial position on the landscape, procedures and software for inferring salinity from EC_a, computer-assisted mapping techniques capable of associating and analyzing large spatial databases, and appropriate spatial statistics to infer salinity distributions in rootzones and changes in salinity over space and time. Descriptions of this assessment system, its theory, software and algorithms and examples of its utility are given in the following references: Rhoades, 1990c, 1992b, 1993b, 1994; Rhoades, et al. 1989a, 1989b, 1990d, 1993, 1996a, 1996, 1997; Lesch et al., 1992, 1995a, 1995b, 1997). The equipment is now commercially available, with improved modifications. The mechanical design of an earlier (second generation) version of this system is described in Carter, et. al. (1993).

3. Management for Water Quality and Environmental Protection

As explained in Section B, drainage from irrigated agriculture is a major contributor to the salinity of many surface and groundwaters. The agricultural community has a need and responsibility to protect the quality of these waters. It must also maintain a viable, permanent irrigated agriculture. Irrigated agriculture cannot be sustained without adequate leaching and drainage to prevent excessive salinization of the soil, yet these processes are the very ones that contribute to the salt loading of our surface and groundwaters. But surface and groundwater salinity could be reduced, if salt loading contributions from the irrigation processes were minimized or eliminated. The protection of our water resources against excessive salinization, while sustaining agricultural production through irrigation, requires the implementation of comprehensive land and water use policies that incorporate the natural processes involved in the soil–plant–water and associated geohydrologic systems. Appropriate policies in this regard need to be developed and effectively implemented in the worlds irrigated lands to protect associated water resources.

Alternative strategies to consider in decreasing salinity in receiving water supplies affected by irrigation and drainage include: (i) eliminating irrigation of certain polluting lands, (ii) intercepting point sources of drainage return flow and diverting them to appropriate disposal sites or treatment facilities, (iii) reducing drainage by reducing the amount of water lost in seepage and deep percolation and (iv) isolating saline drainage water from good quality water supplies and reusing them for irrigation. Only the last two strategies are discussed herein, primarily the last one. Since some effects of irrigation/drainage are operative at the scale of whole projects and entire geohydrologic systems, management practices for drainage disposal and salinity control should address this larger scale. Therefore, the following several paragraphs also provide a brief review of such information, as a basis for developing appropriate management requirements and establishing relevant policy for controlling water (and soil) salinity.

Minimize Deep Percolation and Intercept Drainage

As shown by Rhoades et al. (1974) and Oster and Rhoades (1975, 1990), the total salt–load discharged from the irrigated rootzone in percolation-water can be reduced by about 2 to 12 metric tons/ha/year as the leaching fraction is reduced from 0.3 to 0.1. Such a reduction in salt return is achieved in three ways. Less salt is discharged with reduced leaching because less irrigation water, and hence less salt, is applied. The percent reduction in salt discharge due to reduced application is 100 $(V_H - V_L)/V_L$, where V_H and V_L are volumes of irrigation water applied with high and low leaching, respectively. Reduced leaching reduces the discharged salt-load still more because the fraction of applied salt that precipitates as minerals (such as calcite and gypsum) in the rootzone region of the soil increases. A further benefit of reduced leaching is that less additional "geologic" salts are "picked-up" by the percolating water from the weathering and dissolution of soil and substrata minerals, because the through–put of drainage water is reduced and the "solvent" capacity of the more saline water resulting from low leaching is likewise reduced. Thus, as compared to high leaching, minimized leaching reduces the <u>amount</u> of salt added to soils and discharged from irrigated rootzones because it maximizes the precipitation of applied Ca, HCO_3 and SO_4 salts as carbonate and gypsum minerals in the soil, and it minimizes the "pick–up" of weathered and dissolved salts from the soil and substrata. While minimized leaching reduces the volume of drainage water and the absolute amount of salt discharged; it increases the <u>concentration</u> of the drainage water. Thus, where the drainage waters can be intercepted before being returned to surface or groundwaters, such reductions of salt load and volume of drainage and increases in salt concentration are of substantial benefit. This is especially true where the drainage waters are to be collected and desalted (Rhoades and Suarez, 1977), as has been undertaken for the drainage effluent from the Wellton-Mohawk irrigation project in Arizona (van Schilfgaarde, 1982) and as might more logically be considered for implementation in the Gulf States where the use of desalting technology is more economically feasible.

On the other hand, minimizing leaching may, or may not, reduce the salinity degradation of the receiving water where the drainage water is returned to a surface or groundwater (Rhoades and Suarez, 1977). A reduction of degradation will generally always occur where saline groundwaters with concentrations in excess of those of the recharging rootzone drainage waters are displaced into the receiving water or where additional salts, other than those derived from the irrigation water per se, are encountered and mobilized in the drainage flow–path and brought into solution by weathering and dissolution processes. Examples are the Colorado River in America and many rivers in Iran where much of the irrigated landscape is underlain with strata which contain high amounts of readily soluble salts. Here, minimizing leaching should substantially reduce the salt load in the rivers downstream of the irrigation projects by reducing the "pick–up" of geologic salts as the drainage water percolates past the rootzone and through these strata and/or displaces highly saline groundwater present in the underlying aquifers which connect with the rivers. For conditions like these, reduced leaching will always reduce the salinity of the river downstream from the project. Similar results will also occur under conditions where the irrigated soils, or underlying substrata, contain gypsum or other forms of mineral–salts, such as are typical of Iraq, Iran and Syria.

On the other hand, for geohydrologic situations, such as the Nile River south of the northern delta and much of the Indus River in Pakistan, where little salt of geologic origin exist in the soils or substrata associated with the irrigated lands, the composition of the deeply percolating drainage water is little changed from that leaving the rootzone. For such cases, the composition of the co–mingled drainage plus receiving water may be about the same regardless of leaching fraction, depending upon the saturation status of the receiving water with respect to calcium carbonate and gypsum and fate of water "saved" by reduced leaching. Thus, minimized leaching will be less beneficial, from the point of view of reducing the salinization of the water supplies receiving drainage water, for the geohydrologic conditions of the irrigated lands associated with the Nile and Indus Rivers due to the absence of major sources of salts in the underlying strata of these lands.

As with river systems, degradation of groundwaters receiving irrigation drainage may or may not be benefited by reduced leaching, depending on the geohydrologic situation. With no sources of recharge other than drainage return flow, the groundwater eventually tends toward the composition of the drainage water, which will be more saline with low leaching (Rhoades and Suarez, 1977). However, reduced leaching slows the arrival time of the leachate. Thus, the groundwater salinity will generally be lower for an interim period of time with reduced leaching (Suarez and van Genuchten, 1981). Low leaching management can continuously reduce degradation of the groundwater, only if other sources of high–quality recharge into the basin exist and if flow out of the basin is high relative to drainage inflow. This matter is one that should be considered in the case of the Nile and Indus River systems, especially the latter, given their extensive groundwater basins and, for the case of Pakistan, the major use made of the groundwaters for irrigation. For more discussion of the effect of drainage management on groundwater pollution see Rhoades and Suarez, 1977.

For the above reasons, the "minimized leaching" concept of irrigation which reduces deep percolation should be adopted and implemented to reduce salinization of water resources associated with irrigation projects, especially in projects underlain by salt–laden sediments (van Schilfgaarde et al., 1974; Rhoades and Suarez, 1977). In addition, saline drainage water should be intercepted. Intercepted saline drainage water can be desalted and reused, disposed of by pond evaporation or by injection into some isolated deep aquifer, or it can be used as a water supply where use of saline water is appropriate. Desalination of agricultural drainage waters for improving water quality is not generally economically feasible even though was implemented for the return flow of the Wellton–Mohawk irrigation project of Arizona, USA. The high costs of the pretreatment, maintenance, and power are deterrents. Only in extreme cases, or for political rather than technical reasons, is desalination advocated (van Schilfgaarde, 1979, 1982).

Intercept, Isolate and Reuse Drainage Water for Irrigation

The ultimate goal of irrigation management should be to minimize the amount of water extracted from the projects good–quality water supply and to maximize the utilization of the extracted portion during irrigation use, so that as much of it as possible is consumed in transpiration (hence producing biomass) and as little as possible is wasted and discharged as drainage. Towards this goal, to the extent that the drainage water from a field or project still has value for transpirational use by a crop (ie., the crop is sufficiently salt-tolerant to be able to extract the water from the saline solution at a rate fast enough to meet its transpirational requirement), it should be used again for irrigation before ultimate disposal (Rhoades, 1977, 1984b, 1984c, 1989). This will reduce drainage and the associated water salinization, as well as increase the available supply of water for irrigation. It will also reduce the waterlogging and overall amount of soil salinity degradation in the associated region.

Drainage waters are often returned by diffuse flow to the water course and automatically "reused". Drainage waters are also sometimes intentionally blended with low-salinity water supplies and then "reused" for irrigation as a means to increase water supplies. Additionally, saline drainage waters are sometimes blended with low-salinity waters before being discharged to good water supplies as part of water quality protection programs. All of these blending activities have serious drawbacks and limitations when one considers the overall effect that such blending has on the total volume of usable water in the combined supply relative to the separate supplies, and they should not be undertaken or advocated as a general method of salinity control (Rhoades, 1989, 1990b). There is considerable misconception about blending that needs to be corrected. A brief case will be made later to show the fallacy of the blending concept as it pertains to the objectives of increasing water supplies and protecting water quality.

A preferred and more fundamentally sound strategy to control the salinity of water resources associated with irrigated lands and to increase effective water supplies for crop growth (or other consumptive uses limited by salinity) is to intercept drainage waters before they are returned to the river (or other low-salinity water supply) and to use them directly for irrigation by substituting them for the low–salinity water normally used for irrigation at certain periods during the irrigation season of certain, suitably salt-tolerant crops grown in the rotation (Rhoades, 1984a, b, c, 1988). When the drainage water is too saline to be used directly for the crop in question, then its potential for reuse is exhausted and it should be discharged to some appropriate disposal outlet or treatment facility. Blending such an unusable water with pure water can not create usability in the saline component of the mix. At best during consumption of the blend, when a volume equal to the purer water is consumed, the original volume of the saline component will be regained (with the same salt concentration and condition of unusability), since salt is not removed in the consumption process. The alternative strategy that I have developed, however, will conserve water, will permit essentially full crop production, as well as minimize the salt loading of rivers that occurs by way of drainage return flows (Rhoades, 1984c, 1989). It will also reduce the amount of water that needs to be diverted for irrigation. Data obtained in modeling studies and in field experiments support the credibility and feasibility of this "cyclic" reuse strategy (Rhoades, 1977, 1984c, 1988, 1989a, b, and c; Minhas et al., 1989, 1990a and b). The strategy is now being tested in a pilot project in Australia (Heath and Heuperman, 1996). A modification of the concept to use the drainage water directly from the shallow water table by deficit irrigation and water table depth control has shown promising results (Ayars, 1996).

There are many different situations where the use of saline water for irrigation in the recommended strategy could be practical. One situation is where high quality water is available during the early growing season but is either too costly or too limited in supply to meet the entire seasons requirements. This situation is common in parts of Pakistan, for example. Where high quality water costs are prohibitive, crops of moderate to high salt tolerance could be irrigated with saline drainage or groundwater, especially at later growth stages with economical advantage, even if this practice results in some reduction in yield relative to that obtainable with a full supply of fresh water. Use of saline water for irrigation reduces the amount of high–quality water needed to grow crops and hence expands the total water–resource base for crop production.

Another situation conducive for such reuse is one where drainage water disposal, or a means of lowering an excessively shallow water table, is impractical due to physical, environmental, social and/or political factors. Reuse of the drainage water for irrigation in this situation decreases the volume of drainage water requiring disposal or treatment, and their associated costs (Rhoades, 1977). Furthermore, a reduction in the drainage volume also reduces the salt loading of the receiving water (Rhoades, 1984b). As an example, many growers in the San Joaquin Valley of California (USA) are presently undertaking reuse of drainage water, at least as a temporary solution, in order to reduce drainage volume and to meet recently imposed discharge restrictions related to protection of the quality and ecology of receiving water systems (Letey, 1994).

The long–term feasibility of using drainage water for irrigation in order to reduce drainage volume would likely be increased if implemented on a project or regional scale, rather than on a farm scale (Grattan and Rhoades, 1990, 1996). Regional management permits reuse in dedicated areas so as to avoid the successive increase in concentration of the drainage water that would occur if the reuse process were to operate on the same water supply and same land area (i.e., in a closed loop). With regional management, certain areas in the region can be dedicated to reuse while other areas, such as up-slope areas, are irrigated solely with high quality water as usual. The second–generation drainage water from the primary reuse area is discharged to other dedicated reuse areas where even more salt–tolerant crops are grown, or to regional evaporation ponds or to treatment plants. Ideally, regional coordination and cost sharing among growers should be undertaken in such a regional reuse system.

In order to plan and implement a successful practice involving the use of the cyclic, dual–rotation strategy for irrigating with saline drainage waters, various other technical, economic and soil considerations must also be addressed. These considerations are discussed elsewhere (Grattan and Rhoades, 1990, 1996).

Avoid Blending Waters for Irrigation or Disposal

As stated previously, the ultimate objective of drainage water reuse and of water quality protection should be to permit the maximum practical benefit (use) to be derived from the total water supply, ie. drainage water plus fresh water. Broadly speaking, water users may be classified into two groups: (1) those who consume the water in the process of use, and (2) those who use it without appreciable consumption. The type (1) users (which include crop producers) will suffer disbenefit in the "blending" philosophy of drainage water reuse and water quality protection. This conclusion will be briefly justified in this section.

Plant growth is directly proportional to water consumption through transpiration. Literature clearly demonstrating this fact and an explanation for its physical and physiological basis are given elsewhere (Sinclair, 1994). From the point of view of irrigated agriculture, the objective is to increase the amount of water available to support transpiration. In considering the use of a saline water for irrigation and in selecting appropriate policies and practices of drainage management to protect water quality, it is important to recognize that the total volume of a saline water supply cannot be beneficially consumed in crop production (ie., transpired by the plant); the greater its salinity, the less it can be consumed before the concentration becomes limiting to growth. Plants must have access to water of a quality that permits consumption without the concentration of salts (individually or totally) becoming excessive for adequate growth. In the process of transpiration, plants essentially separate nearly pure water from the salt solutions present in the rootzone; the pure water is transpired into the atmosphere and the salts are concentrated in the remaining unused soil water. This water ultimately becomes drainage water. A plant will not grow properly when the salt concentration in the soil water exceeds some limit specific to it under the given conditions of climate and management (Bernstein. 1975). This is even true for halophytes (Miyamoto, et al., 1996). Thus, it is obvious that not all of the water in a supply can be consumed by a plant, if the water contains salt. The practice of blending or diluting excessively saline waters with good quality water supplies should only be undertaken after consideration is given to how it affects the volumes of <u>consumable (usable) water</u> in the combined and separated supplies.

Various case-examples have been given in detail elsewhere to justify and illustrate some of the preceding conclusions (Rhoades, 1989; Rhoades and Dinar, 1991; Rhoades, et al., 1992). The principles illustrated in these case-examples apply equally to river systems in which waters are diverted upstream for irrigation and drainage waters are returned downstream. The case of such a hypothetical river system is also given elsewhere (Rhoades, 1989 and Rhoades and Dinar, 1991). This river-case study showed that the pollution of rivers that occur through the return of drainage waters to them can be avoided by intercepting the drainage return flows, reusing them for irrigation and isolating the ultimate unusable drainage from the river. Additionally, field experiments undertaken to test them have verified them. For the sake of space, I refer you to the following publications for this information (Rhoades, 1977, 1984c, 1988, 1989a, b, and c; Minhas et al., 1989, 1990a and b).

The results of the case-studies referred to above clearly show that blending waters that are themselves too saline for the intended consumptive use with good quality water supplies results in a volume of potentially consumable water in the combined supply that is less than that of the good–quality water fraction itself. The amount of such reduction in usable water will depend upon the relative volumes and concentrations of the low salinity (receiving) water and of the saline waste (drainage) water and upon the tolerances of the crops to be produced through irrigation. Therefore, the merits of blending should be evaluated on a case–by–case basis. In some cases, it may make economic sense to blend and to bear the consequences of the losses of water usability and of potential crop yield when the alternative costs of disposal are much more costly. The principle to be understood in this matter is the following: if a drainage (waste) water is too saline to be solely suitable for the crop in mind, then no additional consumptive-use benefit can be gained from it by blending it with a low-salinity water. But a loss can occur in the amount of such benefit that could have been achieved from the sole use of the low-salinity water for crop production.

Sometimes drainage waters are purposely diluted with a "good–quality" water to meet some specified discharge standard and then returned to a good–quality water supply. But as the above–described studies show, even when a relatively small volume of excessively saline water is incorporated into the larger good–quality water supply, the net result is that a fraction of this latter water is made unusable for transpiration by salt–sensitive crops. Thus it is concluded that blending or diluting drainage waters with good quality waters in order to increase water supplies or to meet discharge standards may be inappropriate under certain situations. Even though the concentration of the blend may appear to be low enough to be acceptable by conventional standards, the usability of the good–quality water supply for growing salt–sensitive crops (or for other salt–sensitive water uses) may be reduced through the process of blending. Each time the salt content of an agricultural water supply is increased, the degree to which it can be consumed before its concentration becomes excessive and limiting is decreased. More crop production can usually be achieved from the total water supply by keeping the saline and fresh water components separated. Serious consideration should be given to keeping saline drainage waters separate from the good–quality water supplies, especially when the latter waters are to be used for irrigation of salt–sensitive crops. The saline drainage waters can be used more effectively by substituting them for good–quality water to irrigate certain crops grown in the rotation after seedling establishment. Reuse of drainage water for irrigation of suitably salt–tolerant crops reduces the volume of drainage water needing ultimate disposal and, hence, the off–site pollution problems associated with the discharge of irrigation return flows.

D. Conclusions and Recommendations

A brief summary of some of the more salient aspects of the material that I have presented above on the matter of irrigation sustainability follows. For other views and opinions, see van Schilfgaarde, 1990; Letey, 1994; Smedema, 1995. For world-wide views on related research needs, see the summary of the NATO workshop on "Sustainability of Irrigated Agriculture (Sustainability of Water Resources Utilization in Agriculture) " prepared by Pereira, et al. (1996).

1. Crop Production Dependency on Irrigation

The demand for food in the world is on the increase and expected to become seriously limiting within the next decades. Irrigated agriculture is presently a major contributor to crop production. It contributes at least one-third of the worlds production and proportionately much more in arid countries like Egypt and Pakistan. The dependency on irrigation in this regard is expected to increase, especially in the Middle and Near East Regions of the world, over this period and beyond. But growth in the expansion of irrigation has dramatically slowed over the past decade or two to a present rate that is inadequate to keep up with the expanding food requirements, especially in these latter Regions. At the same time, presently developed irrigated lands and associated water resources are becoming substantially and increasingly degraded through salinization caused by irrigation and drainage activities. The seriousness of this matter needs to be fully grasped by the responsible leaders and agricultural and water resource managers of the various world organizations and appropriate policies and effective programs need to be developed and implemented to deal with this most serious matter.

2.. Degradational Aspects of Irrigation/Drainage

Irrigated agriculture has resulted in major environmental disturbances and its very sustainability is being questioned in many places in the world. In a number of countries, extensive areas of land have been degraded by waterlogging and salinization resulting from over–irrigation and other forms of poor agricultural management. Somewhere between 20-50% of the irrigated land produces substantially reduced yields because of salinity and waterlogging. Irrigated agriculture has also depleted water supplies, especially readily available surface waters and shallow groundwaters, and has polluted some of them as well. Contamination of water supplies by irrigation is, in many places, posing health risks and drastically increasing the costs of treating waters for domestic and industrial uses, as well as limiting crop production potential. The recreational, aesthetic and habitat values of many water systems and agricultural landscapes have also been degraded by irrigation development and practices. Costly regulations are being placed upon irrigation in some developed countries to reduce its pollutional discharges or to treat its wastes before discharge. Finding a suitable, acceptable place for such discharge is increasingly becoming a, if not "the", major problem concerning the sustainability and viability of irrigated agriculture, especially in some developed countries.

Most of the problems of waterlogging and secondary salinization prevalent in irrigated lands have resulted from the excessive use of water for irrigation due to inefficient irrigation distribution systems and poor on-farm management, and the discharge of "spent" drainage water into good–quality water supplies which are used elsewhere for crop production, or for domestic and industrial purposes. These problems have occurred even where low salinity waters have been used for irrigation. This might lead one to conclude that the use of saline drainage waters for irrigation can only increase these problems. However, this is not necessarily the case. The use of typical, saline drainage waters for irrigation will not result in excessively saline soils with proper management. In fact, the interception of drainage waters percolating below rootzones and the extraction of shallow underlying groundwaters and their reuse for irrigation is recommended to reduce the soil degradational processes associated with excessive deep percolation, salt mobilization, waterlogging and secondary salinization that typically occur in irrigated lands and the water pollution problems associated with their discharge to good–quality water supplies.

In considering the use of a saline drainage water for irrigation, especially with blending approaches, and in selecting appropriate management to protect water quality, it is important to recognize that: the total volume of a saline water supply cannot be beneficially consumed for irrigation and crop production; and the greater its salinity, the less it can be consumed before the salt concentration becomes limiting. It is advised that the practice of blending excessively saline waters with good quality water supplies should only be undertaken after consideration is given to how it affects the volumes of consumable water in the combined and separated supplies. Blending drainage waters with good quality waters in order to increase water supplies or to meet discharge standards is inappropriate under certain situations. More crop production can potentially be achieved from the total water supply by keeping the water components separated. Serious consideration should be given to keeping saline drainage waters separated from the good–quality water supplies, especially when the latter waters are to be used for irrigation of salt–sensitive crops. The saline drainage waters can be used more effectively by substituting them for good–quality water to irrigate certain, suitably salt-tolerant crops grown in the rotation after seedling establishment.

While efforts to prevent excessive environmental pollution and to restore and protect natural ecosystems may require the shifting of some water away from agriculture, it is concluded that the implementation of management practices to conserve water, to reduce deep percolation and to avoid the disposal of drainage wastes into good water supplies will go a long way towards minimizing these problems and needs. The goal of increasing food production and conserving water can, and realistically must, be achieved by improving water use efficiency in our presently developed irrigated lands. Getting the fraction of these lands that are presently degraded back into productive condition is essential, both from the view of increasing food production and conserving & protecting the quality of our limited water resources.

3. Management Principles, Strategies and Practices to Control Salinity

An integrated holistic approach is needed to conserve water, prevent soil salinization and waterlogging and to protect the environment and ecology. Firstly, source control through the implementation of more efficient irrigation systems and practices should be undertaken to minimize water application and to reduce deep percolation. Unavoidable drainage waters should be intercepted, isolated and reused to irrigate a succession of crops of increasing salt tolerance, possibly including halophytes, so as to further reduce drainage water volumes and to conserve water and minimize pollution, while producing useful biomass and habitat. Conjunctive use of saline groundwater and surface water should also be undertaken to aid in lowering water table elevations, hence to reduce the need for drainage and its disposal, and to conserve water. Various means should be used to reclaim or to dispose of the ultimate unusable final drainage effluent. Unusable drainage waters should never be discharged into good quality water supplies.

To achieve these goals, new technologies and management practices must be developed and implemented to reduce excessive water uses in irrigation, to conserve limited water supplies and to protect water quality. Efficiency of irrigation must be increased by the adoption of appropriate management strategies, systems and practices and through education and training. Such measures must be chosen with recognition of the natural processes operative in irrigated, geohydrologic systems, not just those on– farm, and with an understanding of how they affect the quality of soil and water resources, not just crop production. Some practices should be used to control salinity within the crop root zone, while other practices should be used to control salinity within larger units of management, such as irrigation projects and river basins. Additional practices should be used to protect offsite environments and ecological systems – including the associated surface waters and groundwater resources. The "on-farm" practices usually consist of agronomic and engineering techniques applied by the farmer on a field–by–field basis. The "district–wide" or "larger organizational basis" practices generally consist primarily of engineering structures for water control (both delivery and discharge) and of systems for the collection, reuse, treatment and/or disposal of drainage waters.

There is usually no "single–way" to achieve salinity control in lands irrigated with drainage waters and associated waters. Many different approaches and practices can be combined into satisfactory control systems; the appropriate combination depends upon economic, climatic, social, as well as edaphic and geohydrologic situations. Thus, no one-set of control practices can be specified as "the" appropriate set for all situations. The latter are too numerous and varied. But some important goals, principles and strategies of salinity management exist that should be used, at both on–farm and project–levels, to develop appropriate "packages" of management to deal with the need for the amelioration of presently degraded lands, to increase water use efficiency in irrigated regions where excessive water is used and to reduce the discharges of drainage water from the projects that pollute and reduce the usability of associated water supplies for irrigation and domestic use. Such goals, principles and strategies for the selection and implementation of control practices are reviewed and discussed in this paper. The new assessment-based technology described herein that utilizes satellite and geophysical sensor technologies should be included in the "packages" to provide a more meaningful basis for planning, monitoring and managing soil salinity than the traditional methods which are based on leaching requirement and salt balance concepts.